Environmental Science & Technology

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Effects of Acidic Deposition and Soil Acidification on Sugar Maple Trees in the Adirondack Mountains, New York

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Supporting Information

ABSTRACT: We documented the effects of acidic atmospheric deposition and soil acidification on the canopy health, basal area increment, and regeneration of sugar maple (SM) trees across the Adirondack region of New York State, in the northeastern United States, where SM are plentiful but not well studied and where widespread depletion of soil calcium (Ca) has been documented. Sugar maple is a dominant canopy species in the Adirondack Mountain ecoregion, and it has a high demand for Ca. Trees in this region growing on soils with poor acid−base chemistry (low exchangeable Ca and % base saturation [BS]) that receive relatively high levels of atmospheric sulfur and nitrogen deposition exhibited a near absence of SM seedling regeneration and lower crown vigor compared with study plots with relatively high exchangeable Ca and BS and lower levels of acidic deposition. Basal area increment averaged over the 20th century was correlated ($p < 0.1$) with acid−base chemistry of the O_a, A, and upper B soil horizons. A lack of Adirondack SM regeneration, reduced canopy condition, and possibly decreased basal area growth over recent decades are associated with low concentrations of nutrient base cations in this region that has undergone soil Ca depletion from acidic deposition.

INTRODUCTION

High levels of atmospheric sulfur (S) and nitrogen (N) deposition have substantially damaged ecosystems in the Adirondack Mountains of New York.[1] Efforts to quantify damage have largely focused on aquatic effects.[2] However, limited recovery of surface water acid−base chemistry in response to large (>40%) decreases in S deposition over the past two to three decades has been attributed to depletion of soil calcium (Ca) and other base cations that may be ongoing despite declining acidic deposition.[3,4] Availability of soil Ca has also been linked to changes in terrestrial faunal and vegetation communities in Adirondack hardwood forests.[5]

Received: February 7, 2013
Revised: September 20, 2013
Accepted: October 8, 2013

Sugar maple (SM; *Acer saccharum* Marsh) is one of the major deciduous tree species of the northern temperate forest and is the second most common tree species in the Adirondack ecoregion with 14.8% of total basal area, exceeded only by red maple with 16.4% of total basal area.[6] As a dominant species in many Adirondack forests, SM contributes greatly to autumn foliage color, provides high-quality hardwood for furniture and flooring, and supports a vibrant maple syrup industry, which dates back to pre-European settlement.[7] Associations between the presence of SM and various soil characteristics have previously been reported elsewhere.[8] Lovett et al.[9] demonstrated that this species plays an important role in nutrient cycling in northeastern forests insofar as it promotes the formation of nitrate (NO_3^-) in soil via nitrification and enhances NO_3^- leaching in drainage water. Sugar maple is also known to have a high demand for soil Ca.[8−12]

Fertilization with dolomite resulted in the recovery of a SM stand on the Allegheny Plateau of Pennsylvania where canopy dieback and elevated mortality were underway.[13] High tree mortality in northwestern Pennsylvania was attributed to a lack of resistance to defoliating insects at sites where soil Ca and magnesium (Mg) availability were naturally low[10] and had likely been reduced by acidic deposition during the preceding three decades.[14] Horsley et al.[10] proposed that acidic deposition reduced supplies of nutrient cations, thereby lowering the ability of the trees to withstand stresses, including drought, freeze−thaw cycles, and insect infestation, although atmospheric deposition of N has recently been associated with increased growth of SM elsewhere in the northeastern U.S.[15] Reduced levels of crown dieback and a near doubling of basal area increment (BAI) was demonstrated 10 years after lime application in a base-poor northern hardwood stand in Quebec.[16] A regional assessment of the relationship between imbalances of nutrient cations and SM decline in the Allegheny Plateau showed that poor tree health was correlated with low concentrations of foliar Ca and Mg. Trees in Pennsylvania appeared to be less prone to decline where Ca and Mg supplies were high.[11] Vigor increased on low base cation sites treated with limestone.[13,16] In the study plots outside of the Allegheny Plateau, however, defoliation and high mortality were not occurring, suggesting that these areas were not affected by decline.[11]

Research to date on relationships between soil Ca availability and SM has focused primarily on growth and condition of canopy trees, but depletion of Ca may also affect regeneration. Fertilization with Ca substantially increased seed production in the Allegheny experiment,[13] and Ca fertilization of low-Ca soils in the White Mountains of New Hampshire increased germination and two-year survival of seedlings.[17] Sugar maple seedlings planted in a Ca-treated experimental watershed had higher survival than seedlings in the more acidic reference watershed.[18] The strength of the observed Ca addition effects on SM regeneration depended on soil characteristics; Ca application amount; and interactions with leaf litter cycling, weather, and pathogens. Regional assessments relating Ca availability to SM regeneration have not been published.

In the research reported here, the effects of acidic deposition and soil acidification on the canopy, growth, and regeneration of SM trees were investigated in the Adirondack Mountains. Our objective was to test the hypothesis that soil measurements associated with Ca availability are related to regeneration, crown condition, and BAI of SM over this 25,000-km^2 region where SM are plentiful but have not been extensively studied, and where widespread depletion of soil Ca by acidic deposition has been documented.[3,4,19] This hypothesis derives from the premise that depletion of soil Ca is negatively affecting the success of SM in this region where it is a primary tree species.

■ METHODS

Study Site Selection. Fifty plots with SM common in the canopy were established within 20 small watersheds (<100 ha) that were selected to represent a 10-fold range of Ca availability based on the chemistry of streams and soils determined in previous studies.[20,21] See the Supporting Information regarding watershed selection.

Watersheds were selected through a randomized process based on the sampling design of the Western Adirondack Stream Study (WASS),[22] which provided an assessment of stream acidification for 565 small watersheds in the western Adirondack region through the sampling of 200 randomly selected streams. The 50 plots were selected for study of SM condition by ranking the 200 WASS study watersheds according to streamwater base cation surplus value,[22] reflecting the supply of Ca and other base cations. The watersheds were then divided into 20 groups that maintained their ranking. Watersheds were excluded if they did not contain sufficient SM trees to establish a 20 m × 50 m plot that included at least eight SM in the canopy. Watersheds were also excluded if it was apparent that logging had occurred within the past three to four decades. At least one watershed met these requirements in 15 of the 20 strata. If more than one watershed was appropriate within a stratum, selection was random. Most of the 15 selected WASS watersheds had streams that were acidified to varying degrees, so 5 additional watersheds (4 outside the WASS study area) were specifically selected to provide soils with relatively high calcium availability.

Two or three 50 m × 20 m plots that included SM trees were established in each selected watershed. The plots reflected the two or three predominant landscape types with respect to vegetation and topography within each watershed. Landscape characteristics were evaluated through the use of geographic information system (GIS) databases, aerial photography, and field reconnaissance to select locations that were generally representative of each watershed, based on slope, hillslope position, aspect, and forest composition.

Through the plot selection process, we incorporated the well-represented range of soil Ca availability[3] and most of the variation in elevation and longitude where SM grow within the Adirondack ecoregion. These factors are related to variations in both bedrock and surficial geology and also acidic deposition levels in this region. Therefore, the relationships developed between soil chemistry and vegetation measurements in this study can be applied throughout the Adirondack region and perhaps to other similar locations.

Field Data and Sample Collection. All plots were sampled once during the summer of 2009. Vegetation condition was assessed, and samples were collected of tree cores and soil as described below. Atmospheric deposition estimates were derived using a spatial model as described by Weathers et al.[15,23] See the Supporting Information for details regarding atmospheric deposition modeling.

Vegetation Tally. For each SM tree greater than 10 cm diameter at breast height (DBH) occurring within each plot, the DBH and crown position were recorded. One 10 × 10 m sapling subplot was established in each plot for enumeration of saplings between 1 and 10 cm DBH. At each of the five predetermined locations at 10-m increments along the centerline of the overall plot, a 1 m × 1 m seedling subplot was established. Within each seedling subplot, the number and species of each tree seedling were recorded. Minimum specifications for seedling inclusion were that it be at least 5 cm tall and have at least two fully formed leaves. The maximum specification for seedling inclusion was that it be less than 1 cm DBH.

Canopy Condition. The crown condition of each SM tree on each plot was assessed and recorded using the protocols of the North American Maple Project.[24] Crown condition measurements were visual estimates made from ground level. Repeatability and comparability of these measurements were maintained by intensive training of field staff and the use of two people to rate each tree. Details are provided in the Supporting Information.

Mineral Soil Sampling. Three to five small reconnaissance soil pits were opened in each plot. From among these reconnaissance pits, the intermediate location in terms of horizon presence and thickness was selected for full pit excavation and mineral soil sampling. The selected site was excavated into the C horizon. The profile was then described following National Resource Conservation Service (NRCS) protocols.[25]

Representative soil samples were collected from the face of the pit in each of the upper and lower 10 cm of the B horizon. The E horizon, where it occurred, was not sampled. Few of the fine roots occurred below the upper 10 cm of the B horizon and keeping the thickness of this increment constant assured the highest comparability among sampled locations. Analyses presented here focus mainly on O_a, A, and upper B horizons. A total of 10 mineral soil pits were replicated during the course of the field sampling program to quantify local variability in soil conditions.

Organic Soil Sampling. At each of five preselected locations situated along the 50-m plot centerline, opposite the five seedling subplot locations, one 10 cm × 10 cm pin block of forest floor material was collected down to the top of the mineral soil (E or B horizon). Pin block sampling involved placing a 10 cm × 10 cm acrylic square on the soil surface after the fresh litter on the surface had been gently brushed away without disturbing the O_e horizon. Holes along the entire perimeter of the square allowed metal pins to be inserted into the soil, forming a block. The soil block was removed intact using the pins as a guide to cut along the sides with a knife. Once the block was removed, the mineral soil was extracted from the bottom side to produce a cube of organic soil, which was combined with depth measurements to determine volume. The pin-block samples were separated into A, O_a, and O_e horizons and placed in zipper-locked bags by pooled horizon.

Long-Term Growth Rates. We collected partial increment cores (bark to pith) from up to three mature, canopy-dominant SM trees located in each plot (six to nine trees per watershed), depending on availability. Two cores (series) were collected for each tree. All trees sampled were at least 35 cm DBH. Ring-width series were measured using a high-precision (0.0001 mm) micrometer and cross-dated using COFECHA[26] to identify and correct errors based on the master site chronology. After cross-dating and removing poorly correlated series, SM growth in each watershed was represented by 5 to 11 trees resulting in 9 to 22 series.

Mean growth rates were estimated by converting mean raw ring widths (all series per site) into BAI using the bai.out function in the dplR package[27] for Program R.[28] This function converts ring-width series (mm) to ring-area series (mm^2) based on the diameter of the tree and the width of each ring moving toward the pith of the tree, assuming a circular cross section.[29,30]

Laboratory Analyses. All chemical analyses were expressed on an oven-dried soil mass basis (70 °C for O horizons and 105 °C for mineral soils). Analyses included loss-on-ignition (LOI); pH (in 0.01 M $CaCl_2$); exchangeable Ca, Mg, K, Na (unbuffered 1 N NH_4Cl); exchangeable H^+ and aluminum (Al; KCl extraction); and total carbon (C) and N (C/N analyzer). These methods are essentially the same as those of the USDA Forest Service, Forest Response Project,[31] which are typically followed in forest soil studies in the Northeast. Quality assurance accounted for approximately 10−20% of the total sample load and included field replicates, sample replicates, blanks, and reference samples with known concentrations established through repeated analyses and interlaboratory comparisons.

Statistical Analyses. Soil chemistry data were summarized to the plot level as an average of all available data within a given plot for each soil horizon (O_e, O_a, A, and upper B) to develop plot-representative soil chemistry values. Atmospheric N and S deposition were extracted from the spatial deposition data based on the location of the soil pits. Significant differences in horizon-specific soil chemistry and atmospheric N and S deposition between plots where SM seedlings occurred and did not occur were evaluated using one-way analysis of variance. For other analyses related to regeneration, we ranked the plots according to soil chemical condition and applied a five-plot rolling average to the regeneration data. The averaged regeneration data were then evaluated with respect to plot soil chemical conditions. This smoothing technique was used to reduce variability between the plots and allow patterns in the data to be elucidated.

Soil chemistry and atmospheric N and S deposition data were analyzed for significant differences among plots with low and high plot average canopy conditions in the same manner as described above for the regeneration data. Lower B horizon soil chemistry data were included with O_e, O_a, A, and upper B horizons for these analyses. Canopy condition values for individual trees within each plot were averaged to generate plot representative canopy condition values. Plot average canopy conditions were defined as “low”, “medium”, and “high” based on the lower one-third, middle one-third, and upper one-third, respectively, of the data range for each canopy condition variable.

Watershed level ($n = 20$) mean growth rates were calculated based on BAI for the entire site chronology (total length varied by site), the 20th century (1900−1999), the previous 50 years (1959−2008), and the previous 30 years (1979−2008). To evaluate relationships of BAI with soil chemistry measured at each site, we calculated Spearman rank correlation coefficients[32] between each mean BAI period and the 2009 soil variables. Nonparametric correlations were used because soil chemistry variables were non-normal, and the mean BAI estimates over different time periods may have been biased by the choice of time periods and any trends and/or serial autocorrelation present. In estimating correlation coefficients, we used five soil chemistry variables (Al, Mg, Ca, pH, and BS) for each soil horizon (O_a, O_e, A, and upper B). Aggregate (mean) values across soil horizons were also included in correlation analysis with mean growth rates expressed as BAI.

■ RESULTS AND DISCUSSION

At the sites selected for study here, atmospheric S and N deposition were highly correlated with each other (0.98) and also with several of the major soil acid−base chemistry variables (−0.58 to −0.76; pH, BS, and exchangeable Ca and Mg; Table 1). Correlations between S or N deposition and exchangeable Al were substantially weaker (0.18).

Table 1. Spearman Correlation Matrix for the Major Atmospheric Deposition and Soil Chemistry Variables

variable	N dep	S dep	pH	Ca	Mg	Al
S dep	0.98	--				
pH	−0.76	−0.72	--			
Ca	−0.63	−0.58	0.93	--		
Mg	−0.69	−0.65	0.88	0.93	--	
Al	0.18	0.18	−0.36	−0.43	−0.47	--
BS	−0.65	−0.60	0.89	0.93	0.88	−0.60

Regeneration. The acid−base status of soils in plots where SM seedlings occurred (n = 24 to 27 depending on selected horizon) differed markedly from those where SM seedlings were absent (Figure 1). Plots that did not contain any SM seedlings (n = 19 to 23 depending on selected horizon) had significantly lower BS and concentrations of exchangeable Ca in O_a, A, and upper B soil horizons ($p < 0.01$). Plots without SM seedlings were also estimated to be subjected to higher rates of atmospheric deposition of S, N, and S + N ($p < 0.01$). Plots that lacked both SM seedlings and saplings had lower ($p < 0.01$) BS and concentrations of exchangeable Ca and Mg for soil horizons where primary nutrient uptake occurs (O_e, O_a, A) than for these same horizons in the plots that contained SM seedlings. High numbers of American beech (AB; *Fagus grandifolia*) seedlings, and especially saplings, were observed on plots having base-poor soils. Of the 26 plots having B horizon BS < 12%, SM seedlings constituted more than 20% of the total seedlings of all species on only one plot. The comparable statistic for AB seedlings was 11 plots (42% of all plots having B horizon BS < 12%). The relative importance of differences in seed input rate, germination, and other factors in driving observed low regeneration on base-poor soils was not determined.

Plots were ranked based on exchangeable Ca concentrations in the A horizon and classified into 9 bins, with exchangeable Ca concentrations that ranged from 0.3 to 1.2 cmol$_c$ kg^{-1} in bin 1 to

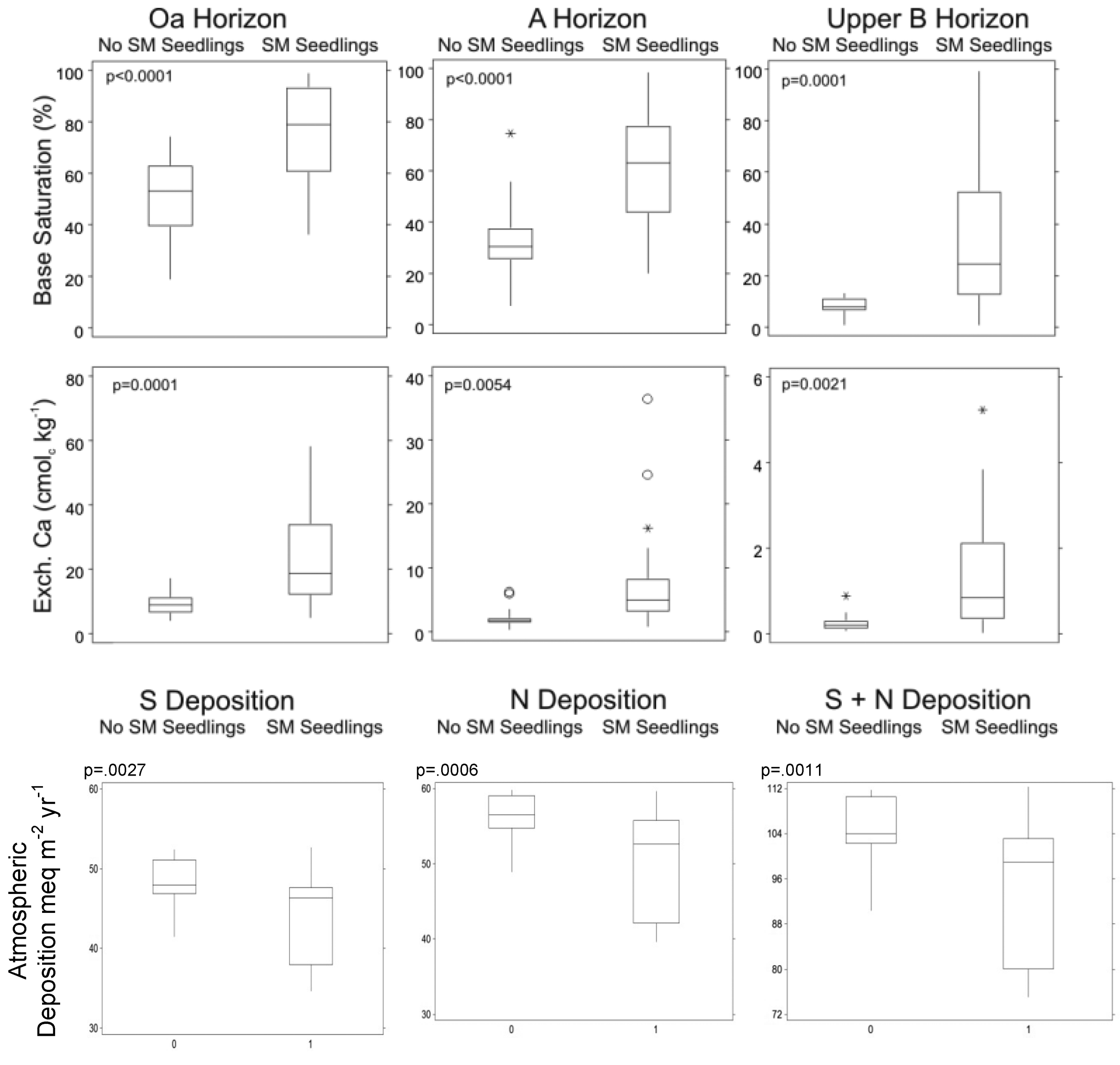

Figure 1. Box and whisker plots of soil % base saturation (BS) and exchangeable calcium (Ca) in three soil horizons (O_a, A, upper B) for two groups of study plots: those containing (O_a: n = 27, A: n = 24, upper B: n = 27) and those not containing (O_a: n = 22, A: n = 19, upper B: n = 23) SM seedlings. Shown at the bottom of the figure is the distribution of atmospheric deposition estimates for the same two groups of study plots. Open circles represent probable outliers (>3 times interquartile range); asterisks represent possible outliers (>1.5 times interquartile range).

16.2−36.3 $\text{cmol}_c\ \text{kg}^{-1}$ in bin 9. In each of bins 1−4 (those having exchangeable Ca in the A horizon <2.5 $\text{cmol}_c\ \text{kg}^{-1}$), the median SM seedling count as a percentage of seedlings of all species was 0, and the 75th percentile was consistently less than 3% (Figure 2).

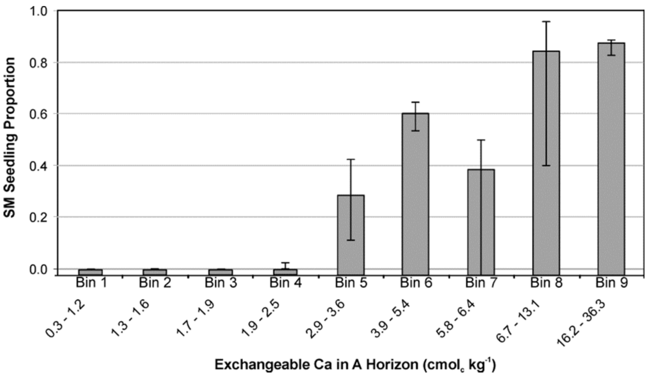

Figure 2. Median (box) and quartile (error bars) sugar maple (SM) seedling count as a percentage of seedlings of all species in groups specified according to the level of exchangeable calcium (Ca) in the A soil horizon. Five plots are included in each bin, except three plots in bin 9, selected in order after ranking plots according to the measured exchangeable Ca value.

In contrast, the median SM seedling count as a percentage of all seedlings on plots having exchangeable Ca higher than 2.9 $\text{cmol}_c\ \text{kg}^{-1}$ was in all cases higher than 28%, and the 75th percentile was consistently higher than 42%. These data indicate a near complete absence of SM regeneration on sites having exchangeable Ca in the A horizon less than 2.5 $\text{cmol}_c\ \text{kg}^{-1}$, despite mature SM being common in the canopies of all plots. Similar results were found for sites having upper B horizon BS above and below 12% (Figure 3), thereby providing a chemical tipping point for estimates of critical load using a process model that simulates the acid−base chemistry of upper mineral soils.[33] The measurement of base saturation serves as a useful proxy for Ca availability because it strongly reflects the ratio of exchangeable Ca to Al, which is correlated with Ca−Al ratios in soil solution.[34]

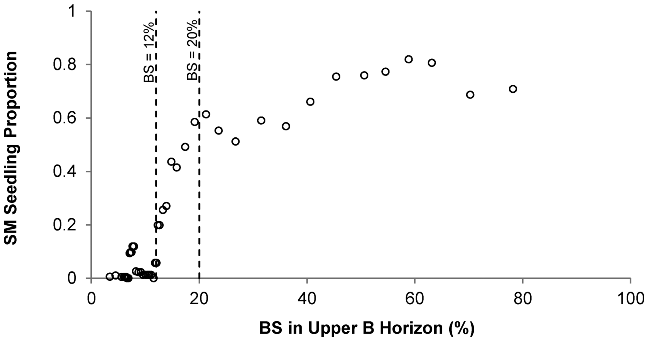

Figure 3. Relationship between the proportion of seedlings that were sugar maple (SM) and soil base saturation (BS) in the upper B horizon. Plots were rank ordered based on soil BS, and a 5-plot rolling average was applied to both the soil BS and the seedling proportion data. Reference lines are added at BS values of 12% and 20%, indicating break points in the sugar maple (SM) seedling proportion response function.

Canopy Condition. Variables reflecting canopy condition were also related to soil chemistry measurements in horizons where primary rooting activity occurs. Canopy vigor was positively correlated ($p < 0.10$) with pH in the O_a and A horizons; with exchangeable Ca in the O_e and upper B horizons; with exchangeable Mg in the O_e, A, and upper B horizons; and with BS in the O_e and upper B horizons (Table 2). When canopies were grouped into categories based on vigor, healthy SM canopies were associated with significantly higher ($p < 0.05$) soil BS and exchangeable Ca in the A horizon (cf., Figure 4). Mean crown transparency was negatively correlated with exchangeable Mg in the upper B horizon ($\rho = -0.44$, $p = 0.0581$), and mean branch dieback was negatively correlated with exchangeable Mg ($\rho = -0.51$, $p = 0.0218$) and exchangeable Ca ($\rho = -0.40$, $p = 0.0781$) in the upper B horizon. Mean discoloration and defoliation were not significantly correlated with soil chemistry (all $p > 0.10$).

Table 2. Relationships between Soil Chemistry and Average Vigor of Canopy-Dominant Sugar Maple within 20 Watersheds in the Adirondack Mountains, NY, Based on Spearman's Rank Correlation Analysis

	soil horizon			
variable	O_e	O_a	A	upper B
pH	0.33	0.41[a]	0.49[b]	0.26
exchangeable Ca	0.49[b]	0.35	0.34	0.51[b]
exchangeable Mg	0.38[a]	0.35	0.41[a]	0.42[a]
exchangeable Al	−0.10	0.21	0.07	−0.15
base saturation	0.40[a]	0.26	0.27	0.47[b]

[a] Significance level: $p < 0.10$. [b] Significance level: $p < 0.05$.

Twentieth Century Growth Rates. Mean growth rates, based on BAI, during the 20th century (1900−1999) were correlated with soil chemistry at the watershed level. Overall, correlation analyses indicated positive growth responses to exchangeable Ca and total BS and to a lesser extent to pH and exchangeable Mg (Table 3). Responses to exchangeable Al were negative but not statistically significant. The weaker Al response may be attributable to the fact that Ca depletion typically precedes Al mobilization.[35] Coefficients and significance levels varied among soil horizons. Mean BAI was most strongly correlated with exchangeable Ca in the O_a and A horizons and with BS in the A horizon. These correlations were weaker for the other horizons and for exchangeable Mg and pH. The O and A horizons represent the primary rooting zone for nutrient uptake in SM stands. These results are consistent with other studies that have linked the availability of nutrient base cations in soil to growth of SM.[8,36]

The 2009 canopy vigor of SM trees was positively correlated with mean BAI during the periods 1959−2008 ($r = 0.48$, $p = 0.03$) and 1979−2008 ($r = 0.46$, $p = 0.04$). Other studies have indicated that poor soil conditions in the Adirondacks have persisted during the previous several decades.[3,4,19] Thus, the strong correlation between canopy vigor and soil Ca availability in 2009 suggests that these soil conditions may have had a negative effect on tree health over the past several decades, resulting in decreased BAI.

Synthesis. Results indicate that the lack of Adirondack SM regeneration, reduced canopy condition, and possibly decreased basal area growth over recent decades are associated with low concentrations of nutrient base cations in a region where acidic deposition has lowered Ca availability.[3,4,19] We are not aware of a single factor other than soil condition that could collectively

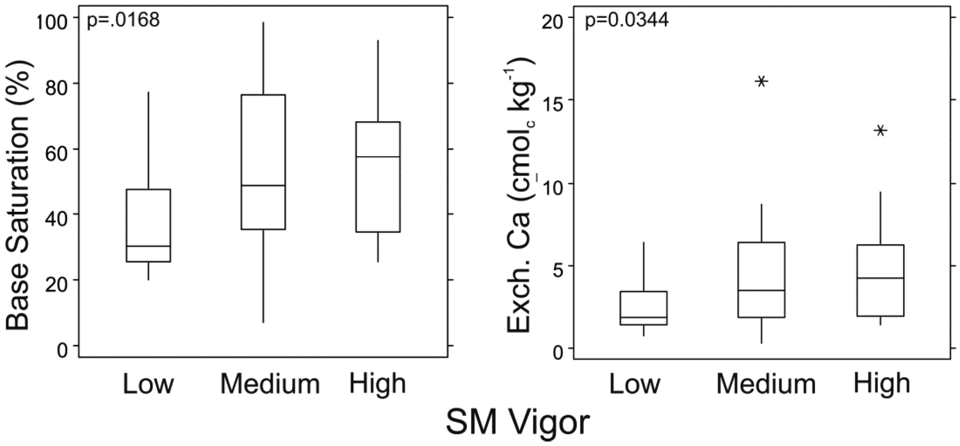

Figure 4. Distribution of soil base saturation (BS; left) and exchangeable calcium (Ca; right) in the A horizon among plots with low, medium, and high average sugar maple (SM) canopy vigor. Vigor classes were defined as follows: 1, dead; 2, severe decline; 3, moderate decline; 4, slight decline; and 5, healthy according to the inverse of the Cooke et al.[24] scale. Low, medium, and high vigor classes correspond with average condition ratings of 2.5−3.1, 3.1−3.5, and 3.5−4.5, respectively. P-values are shown in the top-left of each panel indicating significant ($p \le 0.05$) differences in mean BS and exchangeable Ca values between sites having low and high vigor. Two outlier data points for exchangeable Ca beyond 1.5 times the interquartile distance are not shown.

Table 3. Relationships between Soil Chemistry and Sugar Maple Basal Area Increment (BAI) Measured within 20 Watersheds in the Adirondack Mountains, NY, Based on Spearman Rank Correlation Analysis[c]

	soil horizon			
variable	O_e	O_a	A	upper B
pH	0.41[a]	0.35	0.21	0.27
exchangeable Ca	0.30	0.48[b]	0.50[b]	0.40[a]
exchangeable Mg	0.26	0.38[a]	0.37	0.31
exchangeable Al	−0.14	−0.14	−0.27	−0.06
base saturation	0.30	0.44[a]	0.48[b]	0.38[a]

[a] Significance level: $p < 0.10$. [b] Significance level: $p < 0.05$. [c] Soil variables were compared with mean BAI for each site from 1900−1999.

explain our results for canopy condition, regeneration, and long-term basal area growth, although other factors may influence various individual responses. For example, deer browsing could result in poor regeneration but would not affect the condition of the canopy of dominant and codominant trees and would not explain the association between poor regeneration and soil acid−base status. A previous investigation throughout the Adirondack region did not show a correlation between deer population size and regeneration success of SM, although regeneration varied considerably throughout the region.[37]

The near-absence of SM seedlings and saplings on base-poor soils suggests that community composition of hardwood forests in acid-impacted, low base areas of the Adirondack region may be in the process of shifting away from SM toward other species, such as AB. This differs from the pattern that others[38,39] have documented in the Catskill Mountains to the south of the Adirondacks, where increases in SM abundance have been attributed to the effects of beech bark disease, although this has not been documented on sites where soils are depleted of Ca.

A spatial pattern in overall SM condition was related to both soil chemistry and acidic deposition levels across the Adirondack ecoregion (Figure 5). For this analysis, each sampling plot was scored based on the observed SM condition for seedling regeneration and canopy vigor. A plot was given a point if favorable conditions for SM were observed: presence of SM seedlings and moderate or high vigor. Points were summed to generate an overall condition score for each plot that ranged between 0 and 2. Estimated levels of acidic deposition, BS of the upper B soil horizon, and the overall SM condition score all showed consistent spatial patterns, ranging from high suggested impacts in the southwestern Adirondack region to low suggested impacts in the northeastern Adirondacks. These southwest-to-northeast spatial patterns coincided with previously reported spatial patterns in decreased acidic deposition,[40] increased neutralization capacity of bedrock lithology,[41] and decreased lake acidity,[42] although exceptions with regard to spatial patterns in lake acidity were common. The southwestern portion of the study region generally showed the lowest Ca availability and also experienced the highest levels of acidic deposition. Therefore, this is the area where soil BS below 12% was most commonly observed. This is also the area where regeneration of SM was the least, despite abundant SM in the canopy. This latter finding suggests that depletion of soil Ca by acidic deposition, previously documented in the Adirondack region,[3,4,19] has resulted in base saturation levels that are limiting SM regeneration at southwestern sites, where the presence of canopy SM indicated successful regeneration in the past. It is not known whether this reduced regeneration is due to reductions in seed production or seedling survival or a combination of the two.

Results of this study indicate that SM exhibits relatively poor condition and little to no regeneration throughout much of the western Adirondack region and that the observed conditions are associated with acidic deposition and soil base cation status. Knowledge of areas where SM trees are stressed by soil acid−base chemical conditions may improve the ability of land managers to respond to insect infestations and disease in the face of limited resources.[43] Improved understanding of the relationships among soil acid−base chemical condition and the abundance, growth, vigor, and regeneration of SM is also needed as a basis for evaluation of the critical load of acidic deposition that will be protective of this important tree species, to aid in forest management decisions, and to document effects of acidic deposition on the ecosystem

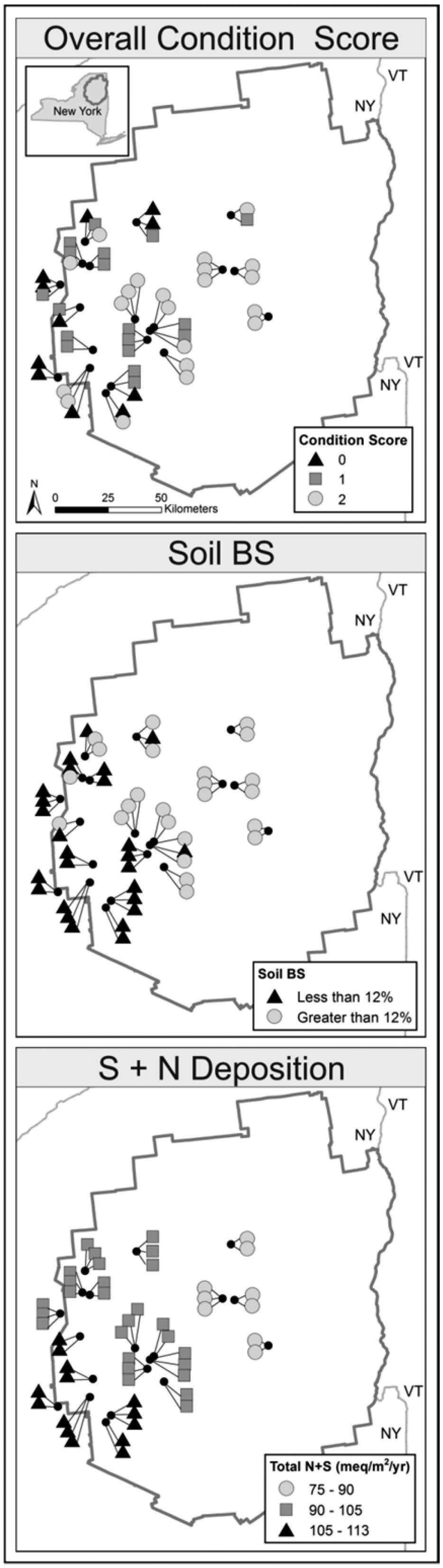

Figure 5. Maps showing the spatial distribution of sugar maple (SM) overall condition score (top panel), soil % base saturation (BS) of the upper B soil horizon (middle panel), and estimated total wet plus dry atmospheric sulfur plus nitrogen deposition (bottom panel) at each of 50 study plots. The condition score was calculated based on the presence of SM seedlings and tree vigor.

services provided by the Adirondack forest and that directly benefit humanity.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Additional detail regarding project methods. This includes information regarding watershed selection, methods for documenting vegetation condition, and methods to estimate levels of atmospheric deposition of sulfur and nitrogen. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This research was funded by a grant from the New York State Energy Research and Development Authority (NYSERDA) Environmental Monitoring, Evaluation, and Protection Program, under the direction of Greg Lampman, to E&S Environmental Chemistry, Inc. Field sampling assistance was provided by M. Brand and M. Leopold.

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